

Exoplanet Spectroscopy: The Hubble Case

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Abstract. The Hubble Space Telescope has recently emerged as the first telescope to detect molecular signatures in an exoplanet via infrared spectroscopy. Molecular spectroscopy of exoplanets is demanding and requires an accurate determination and removal of the instrument systematics. Here we report on our effort to extract accurate exoplanet spectra from NICMOS spectrophotometry. We developed a standardized and highly automated pipeline to remove instrument systematics based on our previous results. We tested the pipeline and find excellent agreement with observation specific implementations. The process of decorrelating instrument parameters from the measured time series is well understood, stable and guarantees reproducible results.

1. Introduction

The first spectroscopic detection of molecular signatures in the infrared transmission spectrum of HD 189733b (Swain et al. 2008) was a dramatic demonstration of the possibility of exoplanet spectroscopy with sufficient precision to identify the presence and quantify the abundance of oxygen and carbon bearing molecules. Now, also the dayside emission spectrum is measured (Swain et al. 2009) and water (H₂O), methane (CH₄), carbon monoxide (CO), and carbon dioxide (CO₂) are identified through spectroscopy in HD 189733b.

The strategy for extracting the spectrum of an eclipsing exoplanet consists of measuring a spectrophotometric time series pre, during and post eclipse. By comparing the flux measured in eclipse with that obtained out of eclipse, we construct a planetary spectrum. Although HST avoids limitations imposed by the Earth's atmosphere, spectrophotometry with NICMOS is subject to systematic errors that must be corrected because they are comparable in size to the expected molecular signatures. A complete description of the data-analysis strategy is described in the supplementary information of Swain et al. (2008) and updates are provided in Swain et al. (2009).

In this proceeding, we present the results of our effort to extract high accuracy near-IR spectra of transiting exoplanets with the NICMOS camera. The analysis is

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based on our previous results but the reduction is now treated as a pipeline, such that the reduction is standardized and automated.

2. Reduction Pipeline Description

The reduction starts from the time series of image files processed by the STSCI pipeline to include all NICMOS standard reductions except flat-fielding (i.e. the CAL extension output). To increase the saturation time of an individual pixel and provide better stability (i.e. averaging over intra-pixel and pixel quantum efficiency is possible), the camera is typically defocused.

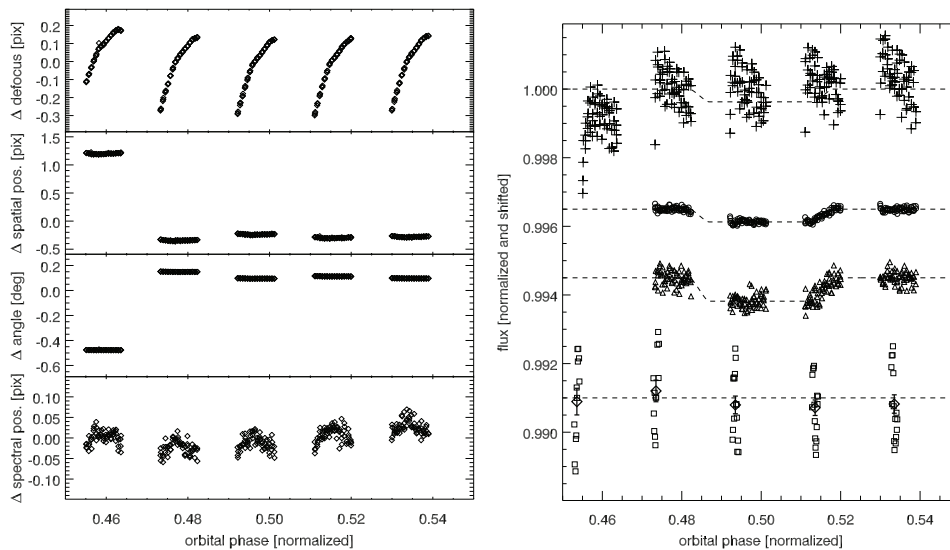


Figure 1. *left*: The time series of the optical state vectors for a typical observation (here shown for HD 209458). *right*: Normalized light curves; from top to bottom: (i) the raw broadband light curve (ii) the calibrated broadband light curve (iii) the calibrated $1.9\ \mu\text{m}$ light curve (iv) contemporaneous MOST visible photometry data, showing both individual and averaged data.

As a first step, we generate an observation-specific flat-field taking into account the color of the illuminated pixels. We use a set of recent on-orbit flats to fit the wavelength dependence for each pixel as a quadratic function. We establish the wavelength for each column of the observation from the calibration exposures and extract the resulting quadratic at the appropriate wavelength by column and apply this correction to the observations. We note that a flat-field correction might be considered optional for differential photometry, since we are only interested in differential changes in time. There are, however, small offsets between different exposures (see further), for which good flat fielding should reduce sensitivity to pixel-to-pixel quantum efficiency changes.

Next, we correct the few bad pixels in the spectrum and do a background correction by fitting unilluminated regions adjacent to the spectrum. Then we determine the *state of the observation*. We fit Gaussians along the spatial direction for each column to determine the width and mean position of the spectrum. These multi-column fits are used to quantify, for each exposure, the angle and position of the spectrum on the

detector as well as a proxy to the defocus. The data is now *homogenized*: we derotate and shift the spectrum to place all observations in a common, pixel-based reference frame. A spatial mask is applied and spectra are extracted by summing in the (new) spatial direction. When multiple orders are present on the detector, the orders are co-added to improve signal-to-noise. As a last step in the extraction method, we determine the displacement in the spectral direction by identifying differential shifts from the edges of the transmission curve.

Time series of the optical state vectors (defocus, position, angle, spectral shift) are shown in Fig. 1. Our assumption is that the light curves have causal connection with these state vectors. Furthermore, we assume that the light curve behavior can be described by perturbations which are linear in these variables. It is clear from Fig. 1, that the position and angle of the spectrum on the detector in the first orbit differs strongly from the other orbits. We, therefore, exclude the first orbit data as a standard precaution in any further analysis, since the linear approach could work poorly for these data.

Following Swain et al. (2008), we correct for instrumental systematics based on the behavior of the optical state vectors, the orbital phase and its square and the temperature of the detector. We do this by using a downhill-simplex method to minimize the residuals in the light curve. We tested the difference with a Gauss-Markov method (as in Swain et al. 2008) and find that both methods provide similar results, but a downhill-simplex method is easier to customize and faster. The standard approach of the pipeline is to do a joint decorrelation of the in and out of eclipse data, although it is also capable of the approach used in Swain et al. (2008), where a model for the instrument systematics is derived from the out-of-eclipse data and interpolated to the in-eclipse section. In the joint decorrelation approach, we provide orbital parameters to the code and it will generate results for the free parameters. The approach is to compute the corrected light curve for trial decorrelations of the instrument systematics and trial model light curves. Minimizing the power in the residuals yields the desired parameters (e.g. planetary radius). We note that our implementation of the decorrelation algorithm allows us to increase the number of state vectors and to do a multi-parameter light curve modeling. Our strategy is, however, always to use the minimum number of variables possible, not to include non-causal parameters or to do over fitting. An example of the decorrelation process is shown in Fig. 1, where normalized light curves before and after correction are shown.

3. Verification of the Pipeline

The data-analysis approach presented here remains largely unchanged from Swain et al. (2008, 2009), but is updated in three significant manners. First the extraction of the spectrum from the time-series has become an automated process. Second, the decorrelation of the instrument parameters is now fully pixel based rather than average pixel based, as in the past. The advantage is that pixel sensitivities are better sampled and that we can work with the full, although oversampled, spectral resolution of the instrument. Third, we now derotate and shift the spectrum to put the observations in a single reference frame.

We tested the new reduction and decorrelation package by re-computing the transmission and dayside emission spectrum of HD 189733b and compare it to the published results in Swain et al. (2008, 2009), which is shown in Fig. 2. Both methods provide

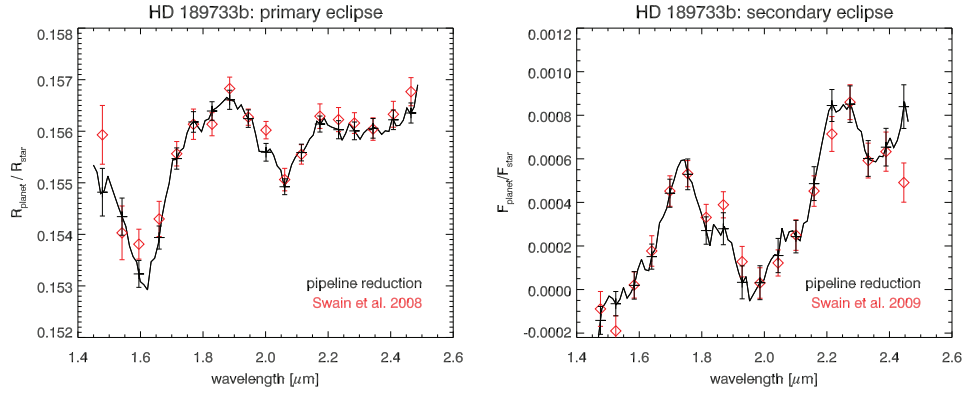


Figure 2. The code was verified by re-computing the transmission (*left*) and day-side emission spectrum (*right*) of HD 189733b.

excellent agreement, with differences between the spectra within the statistical uncertainty of the measurements.

4. Conclusions

Measuring a high signal-to-noise exoplanet spectrum with NICMOS is demanding and requires a proper modeling and removal of the systematics involved. The detection of molecular signatures in the transmission and dayside emission spectra of HD 189733b are a direct confirmation of our ability to achieve the required stability. With the development of our reduction pipeline, we demonstrate that the data analysis method, based on decorrelation of instrument parameters from the measured spectrophotometric time series, is well understood and stable. Our analysis approach remained largely unchanged except for it becoming highly automated, pixel based and placing all observations in a common-pixel based reference frame. Moreover, the decorrelation algorithm has been reimplemented to become more extendable. We tested the pipeline by re-reducing the observations of HD 189733b and find excellent agreement.

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References

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 Swain M. R. et al. 2008, *ApJ*, 960, L114.